SHEAR WAVE WEDGE FOR LASER ULTRASONICS

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INTRODUCTION

Ultrasonic shear waves are a useful tool for determining the mechanical properties of various materials. One example is the use of shear waves to measure viscosity. The viscosity can be determined from the shear wave reflection coefficient. The reflection coefficient from a solid-liquid interface is a function of the viscosity and density of the liquid, as well as the angle of incidence and the material properties of the solid.[1,2]

Laser generated ultrasound has great potential in applications where it is difficult or impractical to use a contact transducer. These applications include those in high temperature and corrosive environments.[3,4] This study deals with developing a technique to measure the viscosity of high temperature, and possibly corrosive, liquids such as molten glasses and metals. However, the work presented here is part of a feasibility study and the experiments have been conducted at room temperature. Future advances and modifications of the technique will adapt it to these more hostile environments.

The advent of in-plane interferometers for detection [5] has made the use of laser generated shear waves more attractive as shown in a recent article by Zhang, *et al.*[6] However, in this article a technique is presented in which the laser generated shear waves can be detected with an out-of-plane detector. Although the work discussed here uses a longitudinal mode, piezoelectric transducer, the use an out-of-plane interferometer is planned in future experiments.

In the following section, an aluminum wedge is described which was used to determine the reflection coefficient of laser generated shear waves. Also, a simple experiment is discussed in which laser generated ultrasound is detected using a longitudinal piezoelectric transducer. The shear wave portion of the signal is analyzed to determine the viscosity of various liquids in the range of viscosities from 50 to 400 poise. In the final section the results are discussed along with the future directions of the research.

SHEAR WAVE WEDGE

Expressions for the directivity patterns of shear waves produced by pulsed laser sources in the thermoelastic regime have been derived and presented elsewhere.[3,4] They are basically a function of the material properties, specifically Poisson's ratio, and are independent of frequency. Fig. 1 shows the directivity pattern for shear waves for a thermoelastic source in aluminum. A distinctive feature of the directivity is the narrow lobe directed at an angle of approximately 30° to the surface normal. For the ablation regime the lobe broadens with most of the energy directed at approximately 35°. In addition to the widening and shifting of the lobes, the transition from the thermoelastic to ablation regimes is accompanied by a change in phase of the particle motion.[3,4]

Review of Progress in Quantitative Nondestructive Evaluation, Vol. 15
Edited by D.O. Thompson and D.E. Chimenti, Plenum Press, New York, 1996

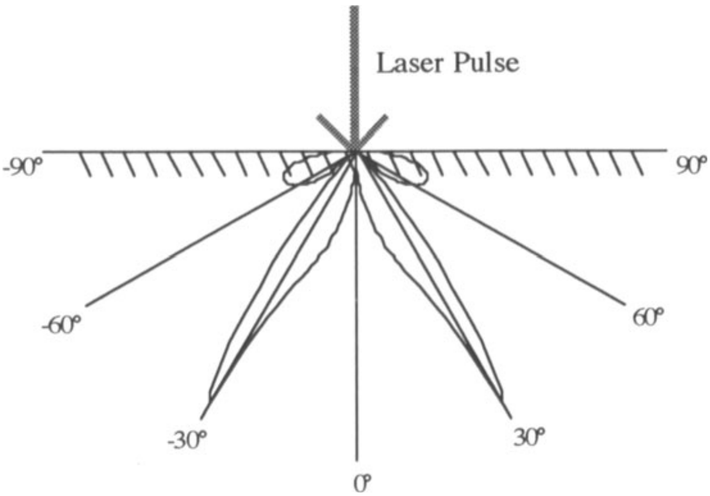

Fig. 1. Directivity pattern for laser generated shear waves in aluminum (c_L = 6300 m/s, c_S = 3100 m/s).

Fig. 2 shows the in-plane and out-of-plane displacements due to an incident shear wave, as a function of the angle of incidence up to the critical angle, on a stress free surface. When a vertically polarized shear wave is incident on a stress free surface both a shear wave and a longitudinal wave are reflected. However, for angles larger than the critical angle, which is 29.5° in aluminum, the wavenumber of the longitudinal wave is complex so that it becomes an evanescent type wave. It was decided at this point that the analysis and interpretation of results would be simpler if all angles of incidence were less than the critical angle. However, it might be worth exploring the possibility of exploiting these larger angles.

In order to take advantage of the pronounced directivity at 30°, the opposite sides of a 3.6 cm (1.4 in.) thick aluminum plate were machined so that they would be at angle of 25° to each other. As can be seen in Fig. 3, the laser generated shear wave will reflect off of the aluminum-fluid interface at an angle of approximately 5° from the surface normal. At this angle, most of the particle motion at the interface due to the shear wave will be in the plane of the interface. In order to be sensitive to the viscosity of the liquid the motion should be primarily of a shearing type, which is in the plane of the interface. Although the aluminum-fluid interface is not stress free it seems reasonable from these results to assume the particle motion is primarily in the plane of the interface.

At the detector the angle of incidence for thermoelastically generated waves is approximately 20°, again from the surface normal. As can be seen in Fig. 2, this angle allows for a significant displacement normal to the surface of the specimen. Thus it is not necessary, or even an advantage, to use an in-plane detector.

For the case of the ablation source, the angle of incidence at the aluminum-fluid interface would be approximately 10° so that there should still be a significant component of in-plane motion at the solid-fluid interface. At the detector, the angle of incidence would be approximately 15°. If one were to work primarily in the ablation regime it would probably be desirable to increase the angle of the wedge to approximately 30°.

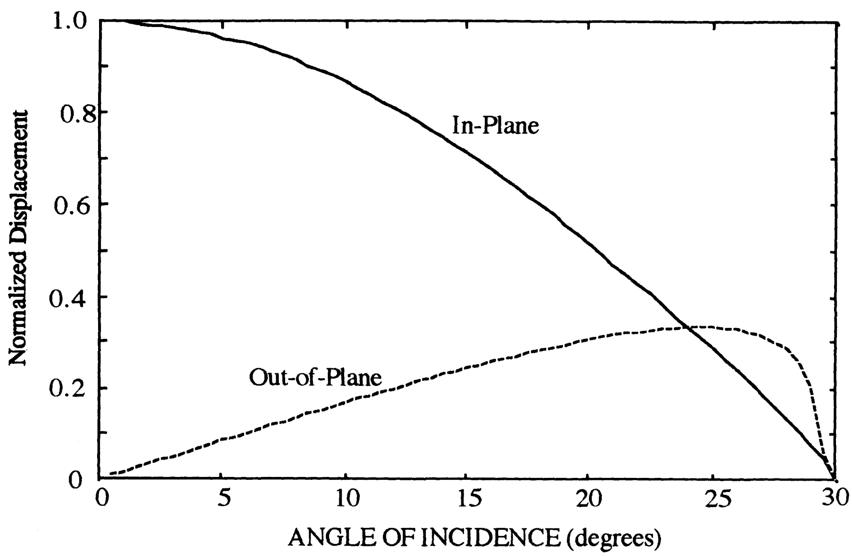

Fig. 2. In-plane and out-of-plane displacements at stress free surface due to incident shear wave.

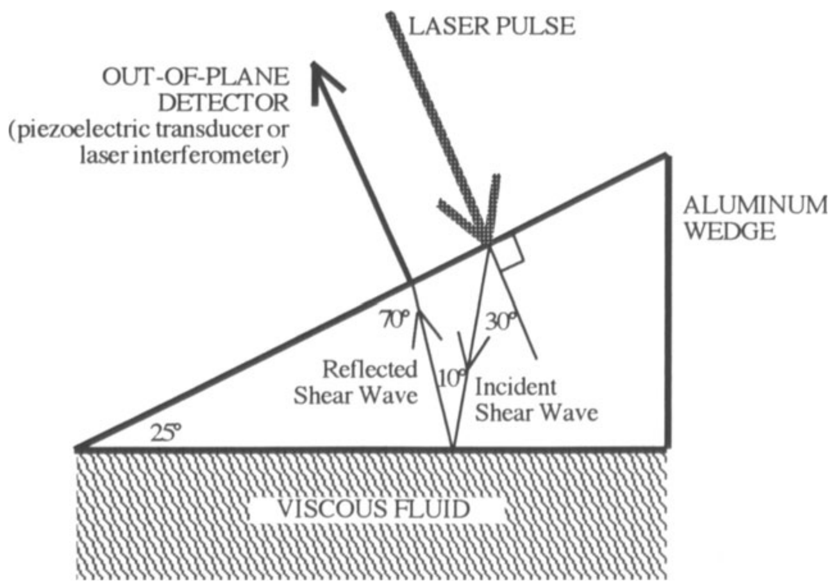

Fig. 3. Schematic of Aluminum Wedge for laser generated shear wave measurements.

In Fig. 4 is shown a signal generated with a pulsed Nd:YAG laser in the aluminum wedge and detected with a 2.25 MHz longitudinal transducer. The arrival of the different parts of the signal are labeled. The wedge that was used in this experiment was approximately 2.5 cm thick at the detector (along a line perpendicular to the solid-fluid interface). A rough calculation shows the distance between the source and the detector to be on the order of 0.5 mm. Indeed, the laser source was positioned near the edge of the 8 mm (0.31 in.) diameter transducer. Calculations using the times of arrival of the longitudinal and shear waves confirm this observation. Optical detection will certainly allow for more precise positioning of the detector with respect to the source.

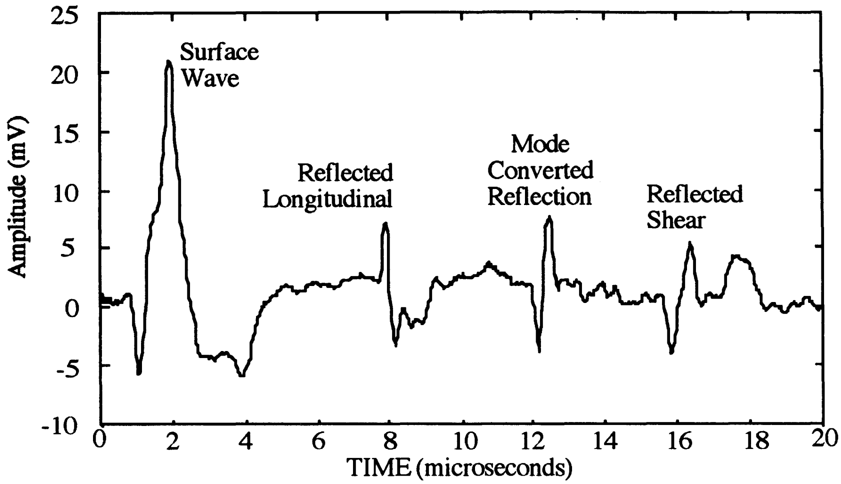

Fig. 4. Laser generated waveform detected with 2.25 MHz longitudinal transducer in aluminum wedge. The viscous fluid was N2000 of Table 1.

Table 1. The viscosity of several NIST calibration fluids measured using the aluminum wedge and compared to their calibrated value. The fluids were calibrated at 25°C and the measurements were made at (uncontrolled) room temperature.

Calibration Fluid	Density (kg/m^3)	Calibrated Viscosity (Poise)	Measured Viscosity (Poise)
N2000	875.3	52	46
N4000	881.2	104	117
N8000	887.3	224	276
N15000	891.3	416	412

The point of optimum thickness on the wedge needs to be chosen. If the wedge is too thin at the points of generation and detection, then the different ultrasonic pulses, longitudinal, mode converted, and shear, overlap each other. But the signal amplitude diminishes as the thickness increases. The waveform in Fig. 4 shows that a reasonable tradeoff has been made between these two competing criteria.

The shear wave portion of the signal in Fig.4 was used to determine the shear wave reflection coefficient associated with the aluminum-viscous fluid interface, which is the reflected amplitude divided by the incident amplitude. In order to determine the incident amplitude, a reference signal was taken with air as the fluid, which has negligible viscosity compared to the viscous fluids used here. Thus, the reflection coefficient for this case is essentially unity and the shear wave amplitude reflected from the aluminum-air interface is basically the same as the incident amplitude for the viscous fluid case. This is, of course, assuming that the geometrical spreading is the same in both cases. However, to account for the variations in signal amplitude due to variations in the pulsed laser energy, the viscous fluid signal was multiplied by a factor so that the amplitude of its surface wave would be equal to that of the reference.

The reflection coefficient was calculated from the Fast Fourier Transform of the two signals. This method and its use in calculating the viscosity, referred to as the magnitude spectrum technique, is described in more detail in another article in these proceedings.[2] The technique was used to calculate the viscosity of several NIST calibration liquids. The results are shown in the Table 1. It should be noted that the measurements were taken at room temperature (which was not controlled) in this experiment and that the viscosity of the calibration liquid was given for 25°C. However, the results shown in the table are very encouraging.

SUMMARY AND DISCUSSION

It has been shown that reflected shear waves can be detected with an out-of-plane detector and distinguished from the other parts of a laser generated waveform. It has also been shown that the viscosity of viscous fluids can be measured from the reflection coefficient. Work still needs to be done to establish the sensitivity of the viscosity measurement.

The next step will be to use an interferometer to detect the laser generated signal. Difficulties are expected to be encountered because the signal-to-noise ratio measured with an interferometer is generally smaller than when using piezoelectric transducers. However, a laser interferometer is essentially a point detector. This will offer the advantage of being able to place the detector in the optimum position with respect to the source. Also, with the piezoelectric transducer used in this experiment there was some degradation of the signal at frequencies over 1 MHz because of spatial averaging across the face of the transducer. This will be avoided with the interferometer.

The experiments will then be conducted at higher temperatures. Since the material properties of the wedge will change with the increase in temperature, a new angle may need to be chosen to take the change into account. Also, at even higher temperatures there may be the need to switch to a refractory metal, such as molybdenum. The wedge would need to be redesigned in this case also.

ACKNOWLEDGEMENT

This work is supported by the United States Department of Energy, grant number DE-FG02-93CH-10575.

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